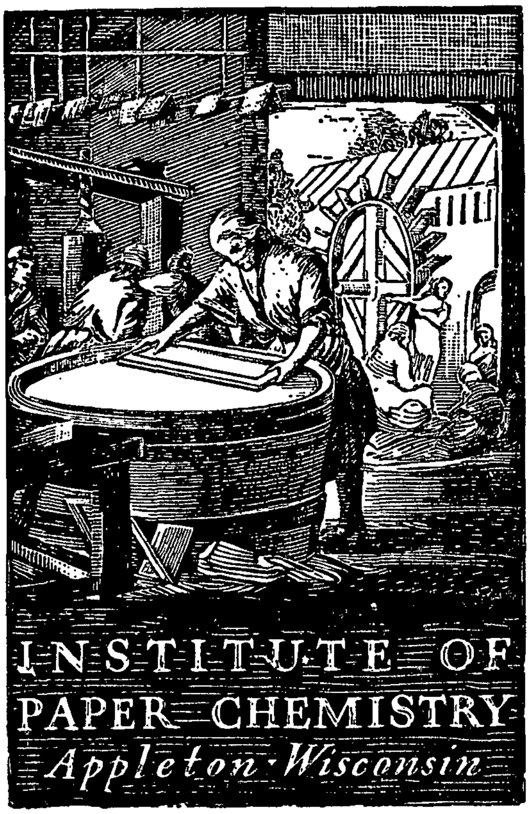

AN INSTRUMENTATION STUDY OF THE COUCH-MULDOON IMPACT FATIGUE TESTER

Project 2033

Progress Report Six

to

MULTIWALL SHIPPING SACK
PAPER MANUFACTURERS

February 10, 1959

THE INSTITUTE OF PAPER CHEMISTRY

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SUMMARY

The Couch-Muldoon Impact Fatigue tester was developed to evaluate the serviceability of paper used in bags and sacks in the situations where it is not convenient or possible to use the drop test. The tester impacts a taut specimen by dropping one-half inch steel balls from selected drop heights onto the specimen until it ruptures. The tester directs the balls to the specimen by means of an orifice which aligns the balls so that they fall within a small area on the specimen. The number of drops to produce failure is considered to be a measure of the impact resistance of the paper.

During the course of the investigation, it was found that the point of impact on a specimen was not consistent between drops, and since there was no means of adjusting the instrument, a modification was developed to accurately drop the balls. An electromagnet picks up each ball and then accurately drops it on the specimen so that all impacts occur at the same point on the specimen.

The objective of this study was to evaluate the instrumental and operational characteristics of the Couch-Muldoon Impact Fatigue tester as a test instrument for the determination of the serviceability of paper used in multiwall sacks. The specific objectives were (1) to determine the instrumental and operational variables of the tester, (2) to determine the effect of

material characteristics on the test results, and (3) to determine the correlation of the Couch-Muldoon data with the results obtained from the drop test, and (4) to determine the operational characteristics of the tester.

The results of the evaluation of the original Couch-Muldoon tester and the modified tester are as follows:

1. Variables of the Tester

A. The size of the impact balls were very uniform. The variation in the diameter was found to be ± 0.05%. It is anticipated that this variation in the size of the balls will not significantly affect the results of the tester.

B. The weight of the balls varied within narrow limits. The variation in the weight of the stainless steel balls used with the orifice release was ± 0.13% of the average weight. The plain steel ball bearings used with the magnetic release varied ± 0.3% of the average weight. This variation in the weight of the balls introduces the same magnitude of variation, 0.13% and 0.3%, in the energy of the impacts.

C. The drop height of the orifice release tester was found to be 0.50 inch higher than the height scale on the tester. The effective drop height of the orifice release was estimated to be equal to the drop height of the magnetic release which was 0.35 inch above the height scale readings. The variation in the spacing between successive height settings was found to be ± 0.01 inch, which would range from ± 0.06 to 0.18% variation, depending on the drop height employed. There was no discernible variation in the drop height due to resetting at a particular drop height.

D. The orifice release did not have a consistent impact pattern. The pattern varied in size, shape, and location from specimen to specimen. The magnetic release had a very consistent impact pattern which does not change in size, shape or location from specimen to specimen.

E. The endpoint of the Couch-Muldoon test is often indefinite and especially so for specimens requiring a large number of drops to produce failure. This variation due to the indeterminacy of the endpoint of the test has been estimated to be ± 2% of the total number of drops required to achieve failure.

2. The Effect of Specimen Material on the Test Results of the Tester.

A. The failure of the paper specimens was a break across the machine direction of the paper. The failure occurred at the center of the impact area when the number of impacts required to produce failure was low. The failure occurred around the edge of the impact area when the number of drops required to produce failure was high.

B. The magnetic release usually required a larger number of impacts to obtain failure in the specimen than the orifice release. The range of the test results and the standard deviation of the test results from the magnetic release also were larger than those of the orifice release.

C. The relationship of the drop height of the drop number was found to be an inverse power function of the form.

$$\underline{N} = \frac{\underline{c}}{\underline{H}^{\underline{a}}}$$

where $\underline{N}$ = the number of drops required for failure,

H = the drop height

<u>a</u> and <u>c</u> = constants

D. The mean of the test results from the magnetic release has greater confidence limits than the mean of the test results from the orifice release due to the higher variability of the test results from the magnetic release. When a sample of 25 specimens of 50-lb. kraft sack paper was tested at a drop height of 12 inches, the magnetic release had confidence limits of ± 3.1 and ± 4.2 drops on the mean value at the 5 and 1% confidence levels, while the orifice release had confidence limits on its mean of ± 1.6 and ± 2.2 drops.

E. The results of a ten-day test indicate that both the orifice and the magnetic release tester give consistent day-to-day results.

F. The orientation of the machine direction of the paper with the specimen holder has no effect on the test results of the orifice and magnetic release tester at the 5% level of significance.

G. The rebound of the balls from the specimen indicated that the energy absorbed by the specimen, at each impact before failure, varied within a range of ± 12%. The energy absorbed by the specimen at each impact was about 40% of the kinetic energy of the ball and the rebound energy was about 60% of the kinetic energy of the ball when testing 50-lb. kraft sack paper using a twelve-inch drop height.

3. Correlation with the Drop Test

Twenty different sack papers were evaluated by the orifice release tester and sacks made from these papers were evaluated with a constant height (4 feet) drop test and a progressive height (2 feet + 6 inch increments) drop test. The correlation coefficients were found to be +0.75 for the constant height drop test and +0.72 with the progressive drop height drop test.

INTRODUCTION

The fatigue failure of metallic materials is defined as a failure occurring as a result of the repeated applications of stress which are lower in magnitude than the ultimate strength of the material (1). Experimentation to determine the nature of fatigue has revealed that nearly all materials except brittle items such as ceramics are affected by repeated applications of stress in much the same manner as metals. Wood, an anisotropic material with different strength values for the in-grain and across-grain directions, shows definite fatigue characteristics when repeatedly stressed (1). The failure of the paper of multiwall sacks when subjected to repeated impacts in actual service or by a drop test may be considered a fatigue type of failure since the failure occurs after repeated stressing by stresses which are below the ultimate strength of the paper.

One characteristic of fatigue failure in all materials is that the laboratory tests which make only one application of load (ultimate strength) cannot predict when the fatigue failure will occur. The fatigue characteristics of a material can be obtained only by testing a representative sample under the desired conditions until a failure occurs. The service life of paper used in multiwall sacks is usually determined by testing sacks, which are made from a representative sample of the paper, with the drop test until the paper fails. However, there is great need for more "practical" tests on the paper because of the cost and time involved in performing sack drop tests as well as the difficulty of interpretation--relating the test results to the properties of the sack paper.

The Couch-Muldoon Impact Fatigue tester has been developed in an attempt to fulfill this requirement for an instrument to evaluate the potential service life of paper in terms of bag and sack performance.

The Couch-Muldoon Impact Fatigue tester was developed by R. de S. Couch and T. J. Muldoon of the General Foods Corporation as a result of their work to develop a test that would replace the drop test for evaluating the potential serviceability of papers for use in bags which were to contain food products (2,3). The literature which has been cited claims that the test results of the Couch-Muldoon tester have a significant correlation to the test results of the drop test.

The fabrication study (4) currently being carried out on behalf of the Multiwall Shipping Sack Paper Manufacturers has indicated that there is a fairly good relationship between the Couch-Muldoon and sack performance as measured by the drop test.

The objective of this study is to evaluate the instrumental and operational characteristics of the Couch-Muldoon Impact Fatigue tester as a test instrument for the determination of the serviceability of paper used in multiwall sacks. The specific objectives are (1) to determine the instrumental and operational variables associated with the instrument, (2) to obtain evaluations of various samples to determine the effect of sample material on the test results, (3) to determine the correlation of the Couch-Muldoon data with the results obtained from the drop test, and (4) to determine the operational characteristics of the tester.

DESCRIPTION OF THE TESTER

The instrument is identified as the Thwing-Albert Couch Muldoon Impact Fatigue tester, catalog number 105-1 and series number 14791. Photographs of the instrument may be seen in Figures 1 and 2 and a diagram of the instrument is shown in Figure 3. The Couch-Muldoon tester evaluates paper by dropping steel balls onto a taut specimen until the paper ruptures. The end point of the test is the impact that causes a rupture in the specimen. The rupture is usually evidenced by a crack in the impact area. The number of impacts required to obtain rupture of the paper is considered to be a measure of the impact resistance of the paper.

The Couch-Muldoon tester is 15-3/4 inches long, 9 inches wide, 28-3/4 inches high, and weighs forty-five pounds. The test specimens for the tester are 4 inches by 4-1/2 inches. The impact balls are dropped at the constant rate of thirty per minute. The instrument may be divided into five functional parts which are the base, the specimen holder, the rebound container, the upper platform with the magazine, and the mechanism for dropping the balls. A description of each part is given in the following paragraphs.

The base, designated with the letter A in Figure 3, is a cast steel platform which supports the entire instrument. It is equipped with one stationary leg and three adjustable legs which permit the instrument to be leveled on any working surface. The electrical on-off switch and a leveling bubble are located on the left side of the instrument base.

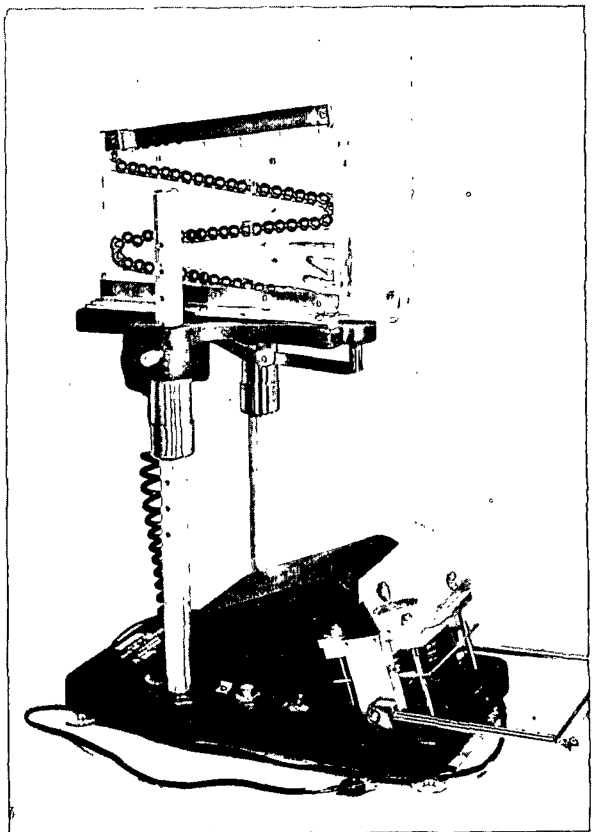


Figure 1

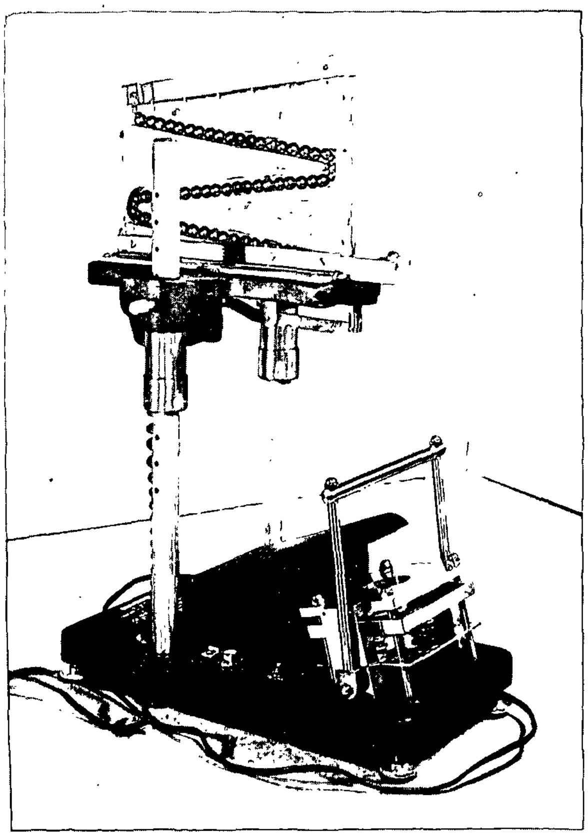


Figure 2

The Couch-Muldoon Impact Fatigue Tester

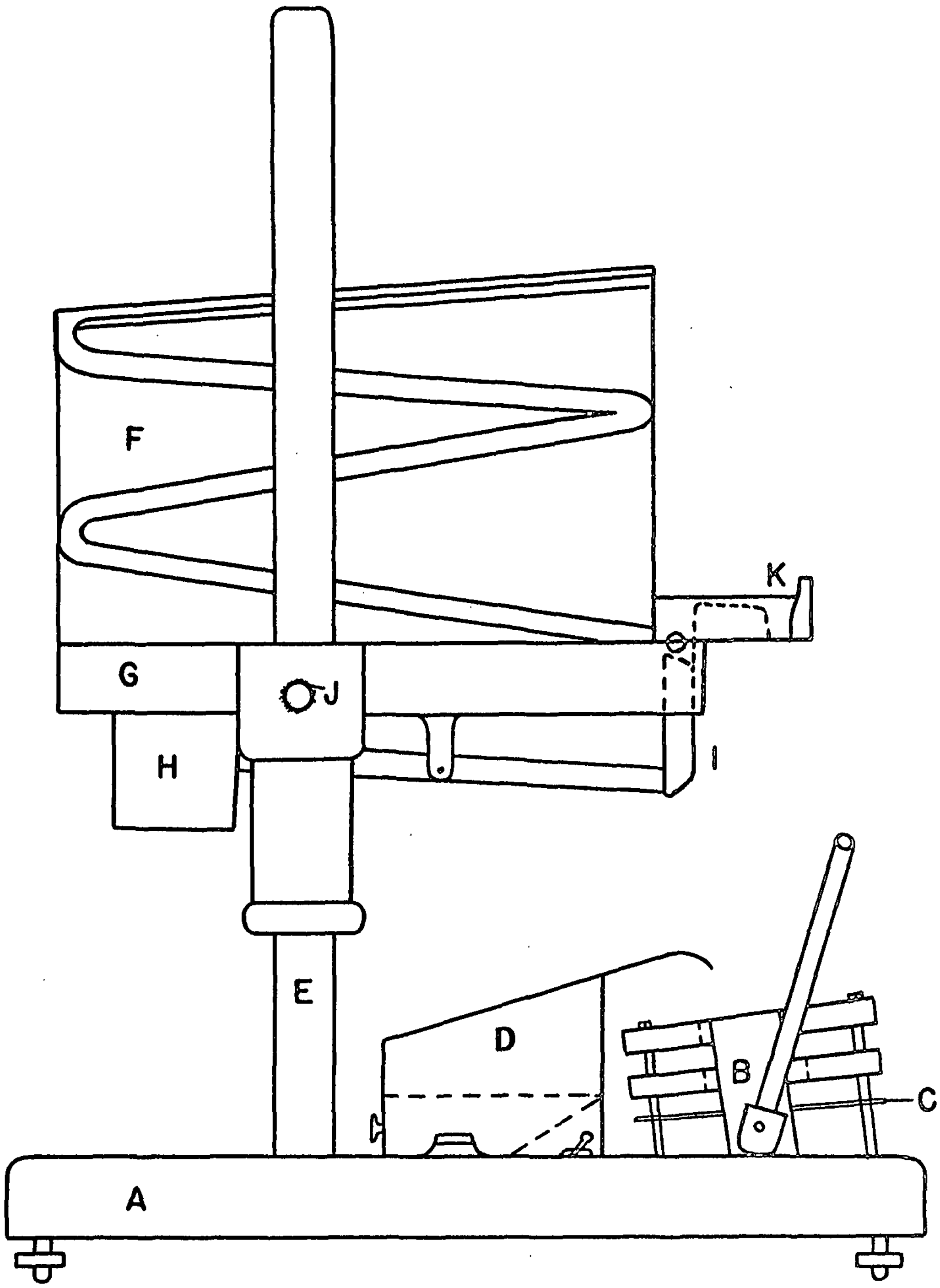


Figure 3. Couch Muldoon Tester

The specimen clamps, B, hold the 4 by 4-1/2 inch paper specimen, and expose an inch and three-quarters diameter circular area of the specimen, which is taut and smooth, to the impact of the balls. The two holding clamps of the specimen holder are shown in Figure 4. These clamps, one fixed and the other movable, are forced together by cams actuated by a hand lever. The fixed upper clamp is 5-1/2 by 4 inches and has a truncated cone projection on its under surface. The bottom clamp is 5 by 4 inches and has a truncated cone depression in its top surface which matches the top clamp. Both clamps have a 1-3/4 inch diameter hole located on the central vertical axis of the cone which is the center of the clamps. The specimen holder is tilted fifteen degrees below the horizontal, toward the rear of the tester, so that the balls rebound from the specimen into the rebound container. A highly polished plate, C, located below the holding clamps, serves as a mirror so that both sides of the specimen may be observed as the test progresses.

The rebound container, which is rubber lined, is identified as D in Figure 3. It is placed immediately behind the specimen holder and collects the impact balls as they rebound from the specimen. There is a drawer in the lower section of the rebound container which facilitates removing the balls from the container and returning them to the magazine.

The upper section of the tester is supported by the two one-inch diameter posts which are a part of the base. The left hand post has holes drilled in it at one-inch intervals which correspond to drop heights of five through sixteen inches. A pin, J, holds the upper section in place with the help of a friction clamp which grips the right-hand post. The magazine, F, is a folded tube type of magazine which holds approximately one hundred

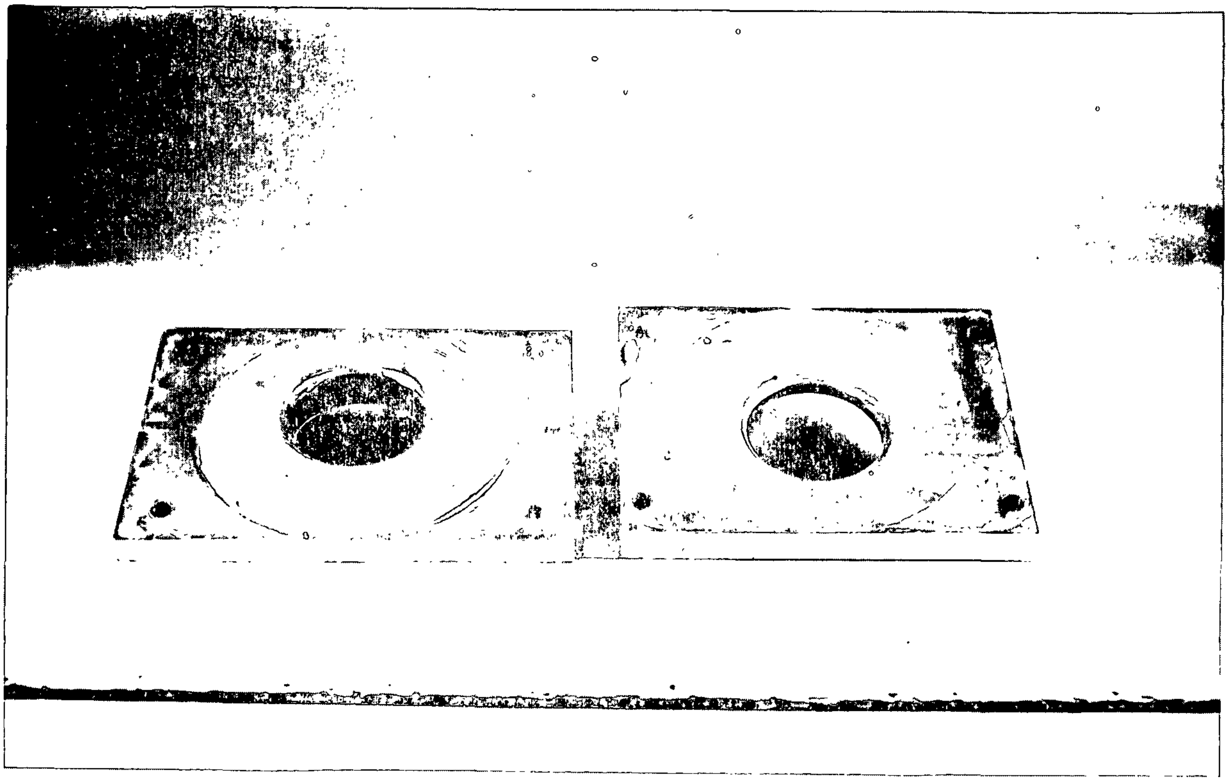


Figure 4. Detail of the Couch-Muldoon Specimen Clamps

one-half inch diameter balls which feed down to the front corner of the magazine by gravity.

The mechanism which individually drops the balls is located on the under-surface of the upper platform. A small synchronous motor, H, operates on 115-volt alternating current. The rotary motion of the motor is converted into vertical oscillatory motion by means of a slotted arm and a crank pin. The plunger, I, is located on the opposite end of the slotted arm and moves up and down removing one ball from the magazine on each cycle. The ball rolls off the top of the plunger into a sloping trough which leads to a tapered hole directly above the specimen. There is a ring within the hole which has a diameter three--thousandths of an inch larger than the balls. This ring serves as an orifice which directs the balls to the impact area on the specimen.

The particular Couch-Muldoon tester used in this study had several construction defects when received. The upright support posts were not vertical to the base but inclined to the right and forward which made it difficult to obtain the impacts at the center of the specimen. The mechanical linkage which converts the rotary motion of the motor to oscillatory motion had to be overhauled after about forty hours of operation when it became inoperative. The mechanical linkage has continued to require occasional adjustments to keep it operating properly. There was no provision made for lubricating the plunger and it frequently binds and sticks because of a lack of lubrication.

VARIABLES OF THE TESTER

An objective of this instrumentation study is to determine the variables of the tester. A preliminary inspection of the instrument suggests that the variables of the tester may be as follows:

The impact balls are directed to the center of the specimen by an orifice which is a tapered constriction which supposedly aims each ball toward the specimen. A significant variation in the size of the balls might cause a variation in the effect of the orifice on the balls. Such a variation may change the impact area on the specimen or it may create a variation in the energy transferred to the specimen by altering the effective drop height of some of the balls. A variation in the energy supplied to the specimen at each drop might alter the number of drops required to produce failure in the specimen.

The weight of the ball is a factor in determining the potential energy of the ball which is equal to the amount of kinetic energy the specimen received at each impact. A variation in the weight of the balls would create a variation in the energy applied to the specimen at each impact and may influence the number of drops required to produce failure.

The height of the drop is the other factor which determines the amount of potential energy in the ball and the amount of kinetic energy transferred to the paper on impact. The tester was constructed so that the drop height could be changed from a height of five inches to a height of sixteen inches. Variation in the drop height may arise from the following conditions:

(1) The drop height scale on the instrument may be incorrect. (2) Consecutive drop height settings may be more or less than an inch apart. (3) The drop height may vary from day to day due to an inability to reset the instrument to exactly the same drop height. (4) The drop height of this instrument may vary from the drop heights of other Couch-Muldoon testers. All of these variations of the drop height will affect the drop number or the interpretation of the test results.

The impact pattern (point where ball impacts the specimen) of the tester may influence the test results. It might be anticipated that if the impacting balls were to impact the paper at precisely the same location, the number of drops or impacts to failure would be less than if the area of impact were more random. The impact pattern should be reproducible and should remain constant in size from specimen to specimen. Furthermore, the impact pattern should remain at the same relative location on the area of the specimens exposed by the specimen holder.

There may be a significant variation in the number of drops due to the indefinite endpoint of the test. This variation may be most noticeable when testing papers that require a large number of drops before a rupture occurs since under these conditions one impact may not completely fracture the specimen. Variation may also arise due to different interpretations of the endpoint by different operators.

MATERIALS

Several materials were used as specimens in evaluating the Couch-Muldoon Impact Fatigue tester. The list includes fifty-pound kraft sack paper, a high-stretch bag paper, engineering tracing paper, 0.003-inch unannealed aluminum foil, and 0.002-inch annealed aluminum foil. The physical properties of the materials used for specimens are tabulated in Table I. All of the paper specimens were preconditioned for at least twenty-four hours at 73 ± 3.5°F. and at less than thirty-five percent relative humidity. The specimens were conditioned at 73 ± 3.5°F. and 50 ± 2% relative humidity for forty-eight hours before any testing was done.

TABLE I

TENSILE CHARACTERISTICS OF THE SPECIMEN MATERIALS

Sample Code	Material	Caliper, in.	Tensile, lb./in.	Stretch, %	Tensile Work, in.lb./in.^{2}
A	50-lb. Kraft sack paper--				
	in	0.005	30.2	1.6	0.33
	across		18.2	4.9	0.66
B	66-lb. Bag paper-- in	0.005	22.6	15.9	1.35
	across		14.8	7.6	0.54
C	38-lb. Tracing paper--				
	in	0.0035	34.0	3.9	0.91
	across		16.1	9.0	1.10
D	0.003 Aluminum	0.003	76.5	2.1	1.45
E	0.002 Aluminum	0.002	19.9	9.9	1.60

MAGNETIC DROP RELEASE

The impact patterns of the orifice release varied from specimen to specimen so that the area of the specimen which was impacted was somewhat more random than desired. The orifice release had no adjustment to correct the drop so a modification was constructed which changed the method of dropping the balls. The modification drops the balls by means of an electromagnet which picks up each ball as it rolls off the plunger and drops it more precisely on the specimen.

DESCRIPTION OF THE RELEASE MODIFICATION

The magnetic-release Couch-Muldoon tester is basically the same instrument as the orifice release tester. Two views of the modified tester are shown in Figures 5 and 6. As may be seen in the photographs, the changes consist of a microswitch, an electromagnet and the associated structure to hold it in location over the specimen, and the necessary electrical power supplies and wiring. A schematic drawing of the electrical circuit of the modification is shown in Figure 7.

A small screw, which is fastened into the core of the magnet and has its outer end cupped to the radius of curvature of the ball, is the point where the ball is held by the magnet. The magnet is energized with a twelve-volt direct current and is de-energized at the moment the ball is to be dropped with a one and one-half volt direct current of the opposite polarity. The one and one-half volt current is required to effectively and quickly break down the magnetic field set up by the twelve-volt current. The change in

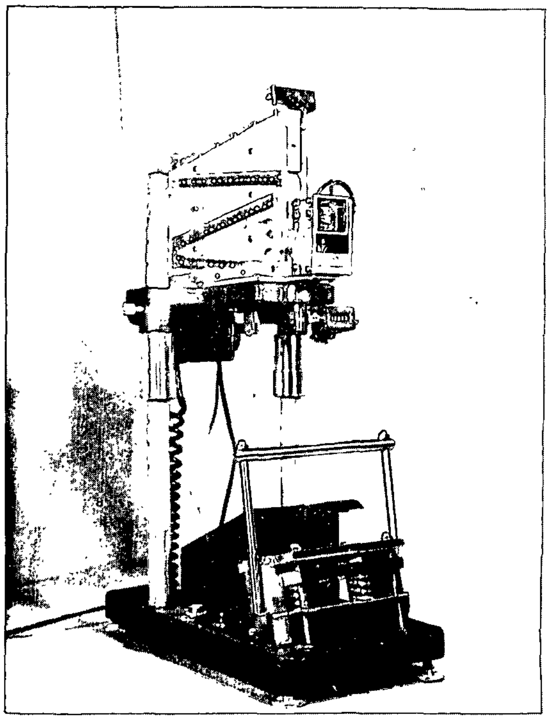


Figure 5.

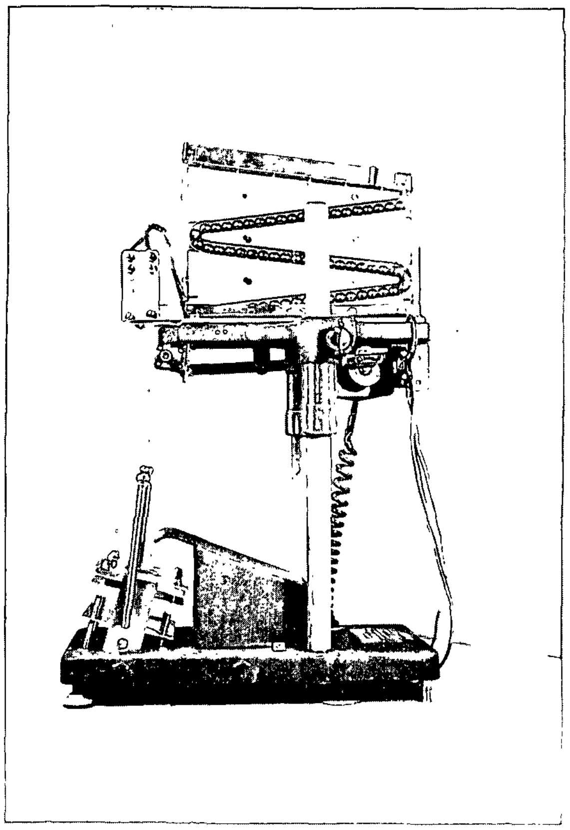


Figure 6.

Couch-Muldoon Impact Fatigue Tester with Magnetic Release Modification

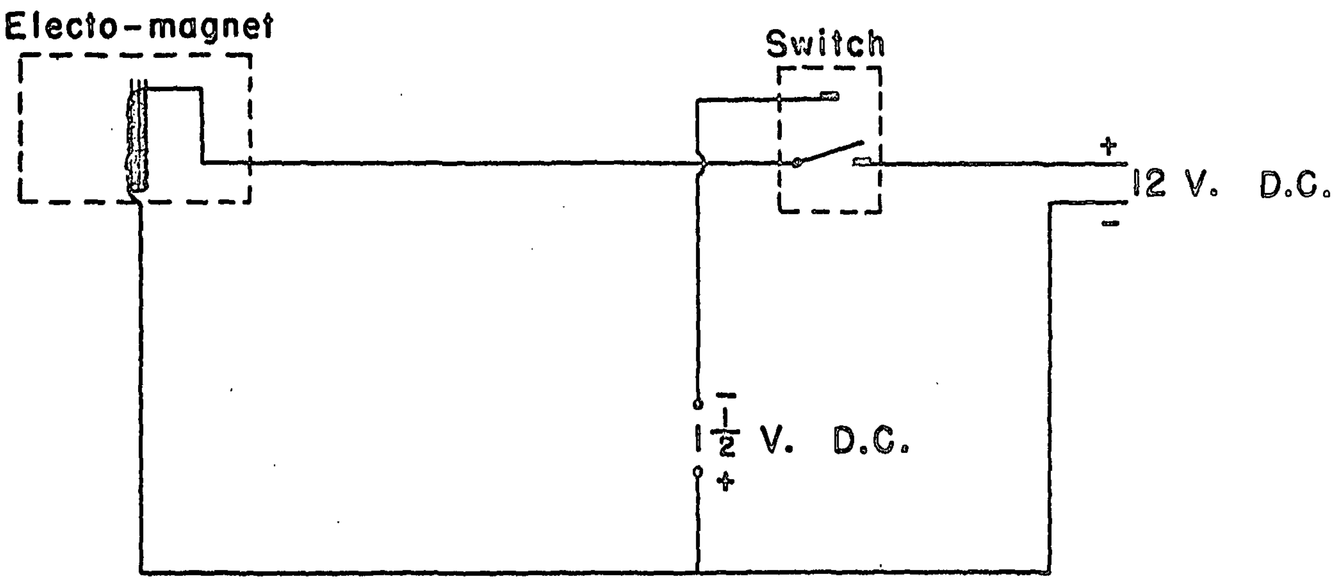


Figure 7

Electrical Diagram of the Magnetic Release Modification current polarity actually forces the ball to leave the pin whereas otherwise it became temporarily magnetized and would not release from the pin. The rapid decay of the magnetic field by the aforementioned means allows the ball to fall freely. If the magnetic field does not collapse rapidly enough, the path of the ball as it drops will deviate from a truly vertical path due to the electrical force acting on the ball as it passes through the magnetic field. The above is an example of a conductor passing through a magnetic field.

The microswitch which is located near the motor on the right-hand side of the tester automatically switches from one voltage to the other as required. The switch is activated by the end of the slotted arm which works with the crank pin to convert rotary motion to oscillatory motion. The entire assembly may be seen in Figure 6 just to the rear of the support post.

The balls which were supplied with the orifice release tester were stainless steel and consequently would not magnetize. The magnetic modification has used one-half inch steel ball bearings in place of the stainless steel balls.

VARIABLES OF THE MAGNETIC RELEASE TESTER

Since the magnetic release was essentially the same instrument as the orifice release, its variables are similar to those of the orifice release tester. These variables include a possible variation in the results of the tester due to the weight of the balls, the height of the drop, the consistency of the dropping method, and the variation due to an indefinite endpoint of the test.

MATERIALS

The materials used in evaluating the magnetic modification were the same as were used in evaluating the orifice instrument. These materials include a 50-lb. kraft sack paper, a 66-lb. bag paper, 38-lb. tracing paper, 0.003-inch unannealed aluminum foil, and 0.002-inch annealed aluminum foil. The paper specimens were preconditioned and conditioned in the same manner as were the paper test specimens for the orifice release tester.

DISCUSSION OF RESULTS

The objective of this study has been to determine the instrumental and operational characteristics of the Thwing Albert Couch-Muldoon Impact Fatigue tester and to determine its ability to predict the service life of paper used in multiwall sacks. Specific objectives have been (1) to determine the variables of the tester, (2) to determine the effect of specimen material on the results of the tester, and (3) to determine the correlation of the Couch-Muldoon data with the results of the drop test.

RESULTS FROM TESTS TO EVALUATE THE VARIABLES OF THE TESTERS

The results of the tests performed to evaluate the variables of the two testers are presented in Table II.

Size of the Balls

The influence of the orifice on the balls may vary as a result of a variation in the size of the balls. A variation in the effect of the orifice on the balls may create a variation in the impact pattern on the specimen and a variation in the effective drop height of the balls which would vary the energy applied to the specimen by each impact. A variation in the impact energy might change the number of drops required to produce failure of the specimen. The stainless steel balls furnished with the orifice release were not suitable for use with the magnetic release because stainless steel does not magnetize. The magnetic release tester used one-half inch plain steel ball bearings. The plain steel ball bearings were used for all the evaluations

TABLE II

PHYSICAL CONSTANTS FOR THE COUCH-MULDOON TESTER

	Orifice Release	Magnetic Release
Ball material	Stainless steel	Plain steel
Size of orifice	0.503 inch	
Diameter of balls, average	0.4997 inch	0.4998 inch
Range of size	0.0005 inch	0.0004 inch
Weight of balls, average	8.4603 grams	8.3453 grams
Range of weights	0.0217 gram	0.0535 gram
Weight after acetone wash	8.4646 grams	--
Range of weight	0.0206 gram	--

Drop heights:

Nominal Drop Height, in.	Drop Height from Orifice, in.	Drop Height from Trough, in.	Drop Height from Magnet, in.
5	4.68	5.49	5.35
6	5.69	6.50	6.35
7	6.69	7.50	7.35
8	7.70	8.51	8.35
9	8.70	9.51	9.35
10	9.69	10.50	10.35
11	10.68	11.49	11.34
12	11.68	12.49	12.35
13	12.68	13.49	13.36
14	13.68	14.49	14.35
15	14.67	15.48	15.35
16	15.68	16.49	16.36

carried out in this study to avoid confounding the comparison of the two methods of release due to possible differences in the two sets of balls.

The diameters of the balls were individually measured with a micrometer to the nearest 0.0001 inch. It may be seen in Table II that the diameter of the two sets of balls were very nearly the same. The average diameter of the two sets of balls differs by only 0.0001 inch. The range in the ball diameters were also very nearly the same. The ranges of the ball diameters were about 0.1% of the average diameter which would indicate a variation of ± 0.05%. Since the orifice is 0.003 inch larger than the average diameter, this small variation in size should not significantly alter the influence of the orifice on the balls.

Weight of the Balls

The weight of the impact ball is one of two factors which determine the energy imposed on the specimen. A variation in the weight of the balls would directly affect the energy level of each impact and, therefore, may influence the number of drops required to break the specimen.

Each ball was individually weighed on an analytical balance. The balls were then washed in acetone and dried. They were again weighed to determine if the weight varied due to handling in use.

The results of the weighing are shown in Table II. The two sets of balls differ in average weight by about one-tenth of a gram and the range of weight of the plain steel bearings was more than twice the range of weights of the stainless steel balls. The range of weights of the plain steel ball bearings was about 0.6% of the average weight while the range of weights of the stainless steel balls was only 0.25% of the average weight. The maximum variation in the impact energy due to a variation of weight in the two sets of balls will be ± 0.3 and ± 0.13%, respectively. The weight of the balls after washing in acetone indicated that there was no significant increase in weight of the balls due to an accumulation of either dirt, oil film, or other foreign material.

Drop Height

The drop height of the impact balls is the other factor in determining the energy involved in each impact on the specimen. The Couch-Muldoon tester is constructed with provision for changing the drop height in one inch increments from a height of five inches to a drop height of sixteen inches. The actual drop height of the ball may differ from the height settings on the instrument and there may be variations in the increments of drop height.

The drop heights of the tester were measured with an inside micrometer to the nearest hundredth of an inch. The results of these measurements are presented in Table II. If the ball moved very slowly through the orifice, the drop height of the orifice release would effectively be the height from the center of the specimen to the bottom of the ball as it left the orifice (Figure 8a). If the effect of the orifice on the ball were negligible, the effective drop height of the orifice release would be the height from the center of the specimen to the bottom of the ball as it left the trough (Figure 8b). The drop height of the magnetic release is measured from the center of the specimen

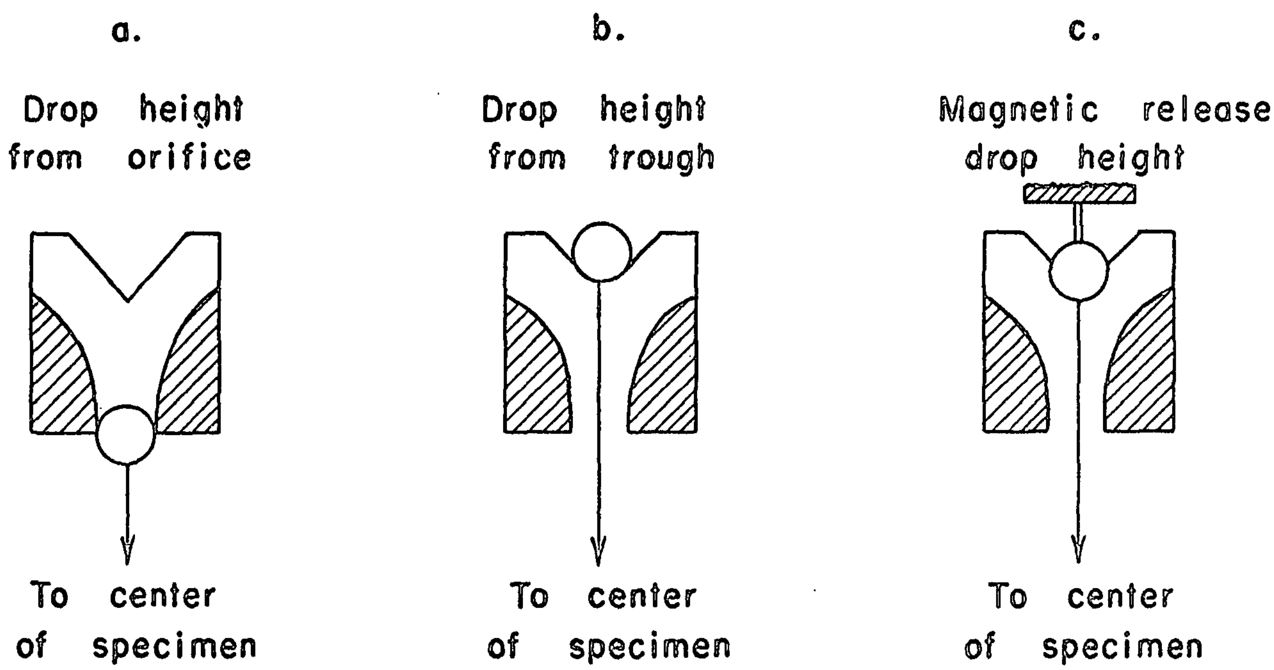


Figure 8

Drop Heights of Couch-Muldoon Tester

to the bottom of the ball as it hangs on the pin of the electromagnet (Figure 8c).

It may be seen in Table II that the maximum drop heights of the orifice release and the magnetic release are greater than the height scale on the tester by 0.5 and 0.35 inch. The maximum drop height of the orifice release is greater than the drop height of the magnetic release but the effect of the orifice on the ball causes the effective drop height of the orifice release to be somewhere between the orifice height and the trough height. The exact degree of influence of the orifice on the balls is unknown. Observation indicates that the effective drop height of the orifice release is closer to the trough height than to the orifice height for the effect of the orifice on the ball appears to be minor. For this study, the effective drop height of the two types of release have been considered to be equal.

The variation in the one-inch distance between consecutive settings may be seen in Table II to be ± 0.01 inch. This variation creates an error in the total drop height which ranges from 0.06 to 0.18%, depending on the drop height setting employed.

The reset ability of the drop height was found to be good. No measurable change in the drop heights was detected when the drop heights were reset.

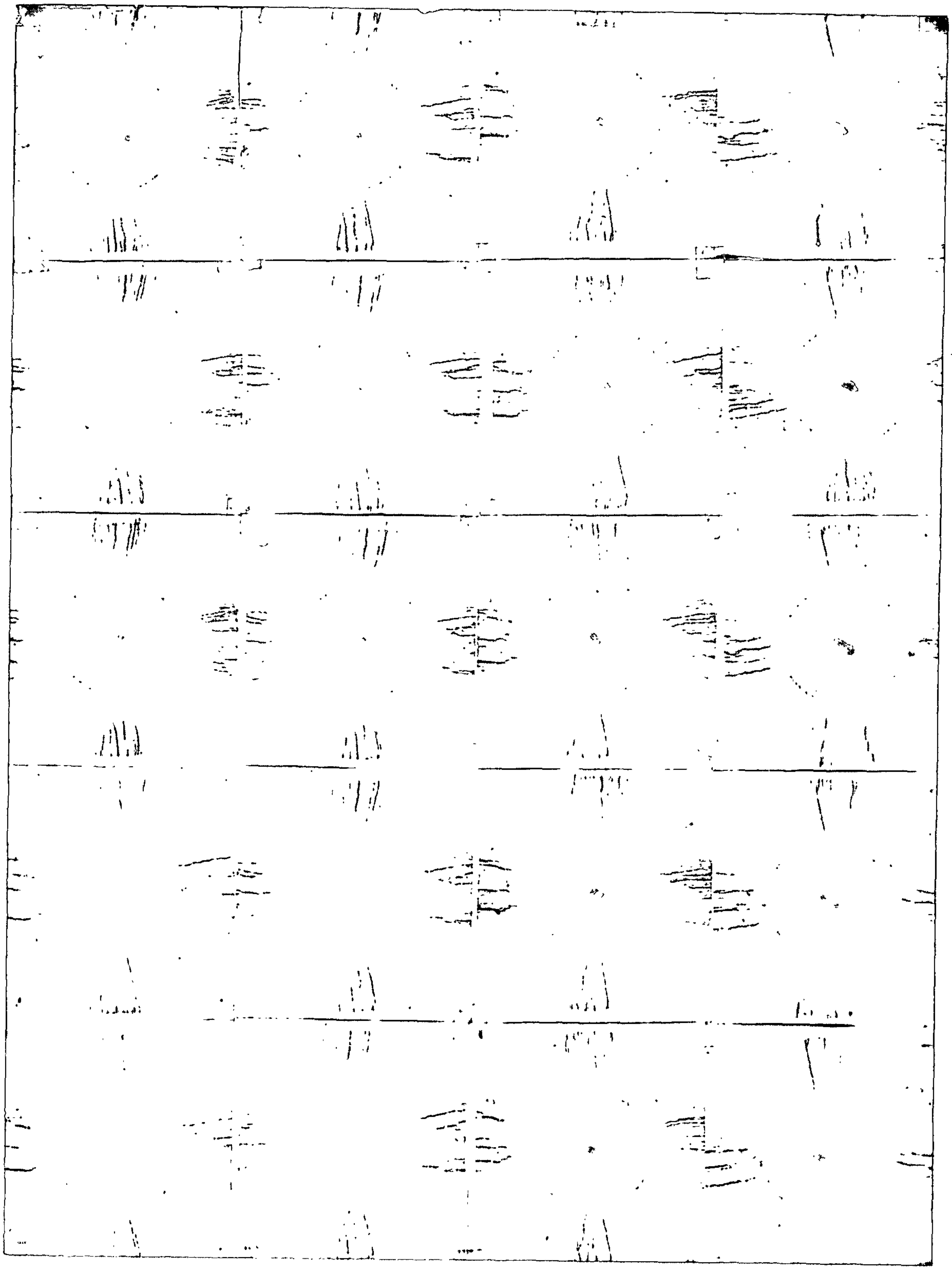
If the drop height varies between Couch-Muldoon testers, it may be expected that the test results will differ. An evaluation of this possible variation is beyond the scope of this study; however, the drop heights presented in Table II may be of aid in comparing the drop heights of other Couch-Muldoon testers with the drop heights of the instrument employed in this study.

Reproducibility of the Drop

The reproducibility of the drop of both testers was observed by obtaining the pattern of the impacts on a specimen consisting of two pieces of paper separated by carbon paper. A series of impact patterns of the two testers are presented in Figures 9 and 10. It may be seen in Figure 9 that the reproducibility of the drop of the orifice release was very poor. Seldom did successive drops fall in the same spot and the impact area was large and it increased in size with an increase in the number of drops. The impact patterns of the magnetic release, presented in Figure 10, show that successive balls impact essentially the same spot on the specimen and the impact area was much smaller than the impact area of the orifice release and it shows little tendency to grow with an increase in the number of drops. The small increase in the area of the impact of the magnetic release as the drop number increased was due to the depression in the specimen which caused the ball to make more contact with the specimen.

End Point Determination

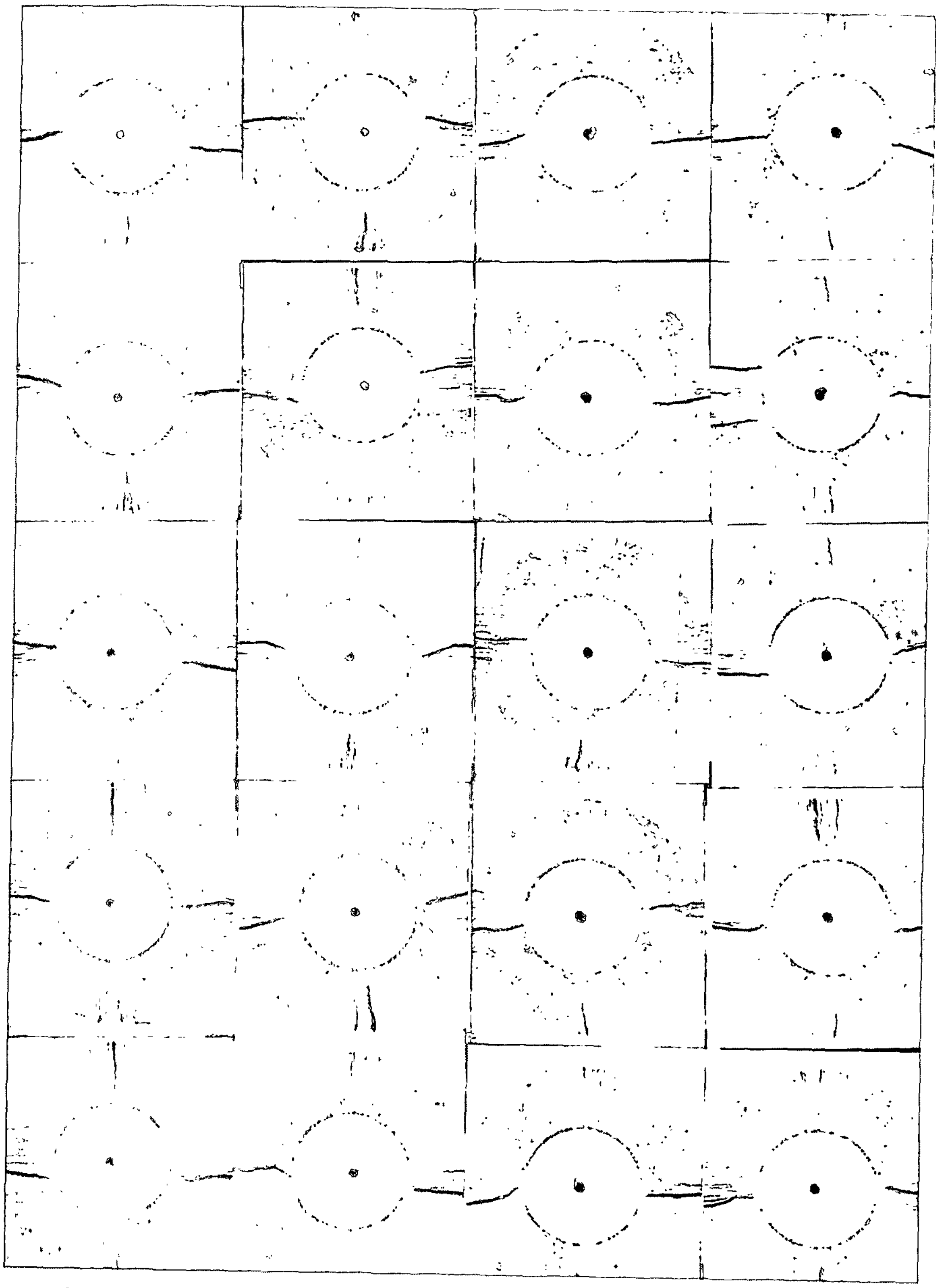
The end point of the Couch-Muldoon test is often hard to determine. This is especially true when the specimen requires a large number of drops



2 Impacts 5 Impacts 10 Impacts 20 Impacts

Figure 9

Impact Patterns of Orifice Release Tester



2 Impacts 5 Impacts 10 Impacts 20 Impacts

Figure 10

Impact Patterns of the Magnetic Release Tester to fracture it, for the failure is not completed in one impact but progresses during several impacts. Some specimens show surface cracks which can be mistaken for complete failure. The endpoint criterion used in this instrumentation study was: a well-defined crack at least half as long as the diameter of the area covered by the impact of a single ball. The variation in drop number due to the end point determination has been estimated to have been $\pm$ 2%. This variation is significantly high at large drop numbers; consequently, definite endpoint standards should be established to guide operators of the Couch-Muldoon tester.

THE EFFECT OF SPECIMEN MATERIAL ON THE RESULTS OF THE TESTER

Tests were performed on several different materials to ascertain the influence of material characteristics on the results of the Couch-Muldoon tester. The results of the tests are presented in Table III.

It may be observed in Table III that within each tester the range and the variability of the test results as measured by the standard deviation vary in magnitude with changes in material. The ranges and the standard deviation of the test results were larger when testing the 50-lb. kraft sack paper (Sample A) and the 66-lb. bag paper (Sample B) than they were when tracing paper (Sample C) was tested. The tracing paper produced a larger range and more variability in the test results than either of the two aluminum specimens. The test results suggest that the range and the standard deviation of the test results may be influenced by the degree of formation of the specimens, since aluminum foil and engineering tracing paper are considered to be more uniform than the sack paper and the bag paper.

A comparison of the test results between release methods in Table III shows that the orifice release usually required fewer drops to achieve failure in the specimens than did the magnetic release. The variability and the range of the test results from the orifice release were also generally smaller than the variability and the range of the data from the magnetic release. The results of the t-test show that the difference between the two means was often significant at the one per cent level.

On the basis of first impressions, it might be anticipated that the results obtained with the magnetic release on a given sample would be lower than the corresponding results obtained with the orifice release. This was not the case, however, and the reason is not clear. It is felt that this behavior may be dependent on a number of factors such as degree of uniformity of the specimen and also the difference in the way the strain may be distributed in the specimen from impact to impact. In the case of the magnetic release, the successive strain may be distributed more uniformly than in the office release.

Nature of Failure

It may be of interest to describe the appearance of the failure which occurs as a result of the impacts. The failure of the paper specimens always occurred across the machine direction of the paper. Two different fracture patterns were evident. The failure of the specimen occurred across the center of the impact area, as shown in Figure 11, when the number of impacts was small. When the number of impacts required for failure was large, the fracture occurred around the edge of impact area as shown in Figure 12. These patterns of failure were most evident with the magnetic

TABLE III

NUMBER OF DROPS REQUIRED FOR SPECIMEN FAILURE

Drop Height in.	Material	No. of Specimens	Orifice Release: Average No. of Drops	Orifice Release: Range of Drops	Orifice Release: Standard Deviation	Magnetic Release: Average No. of Drops	Magnetic Release: Range of Drops	Magnetic Release: Standard Deviation	Orifice vs. Magnetic: Value of t	Orifice vs. Magnetic: Significance
16.35		25	3.1	7.0	1.6	3.6	7.0	1.7	1.08	N.S.
14.35		25	4.4	5.0	1.3	4.6	9.0	2.5	0.36	N.S.
12.35	A	25	7.7	20.0	4.8	7.6	15.0	4.5	0.076	N.S.
10.35		50	14.9	51.0	8.5	22.6	47.0	16.5	2.93	a
8.35		25	31.7	59.0	15.7	49.6	104.0	28.3	2.75	a
6.35		25	77.8	153.0	36.0	323.0	729.0	211.5	5.66	a
16.35	B	50	34.4	61.0	12.5	93.9	320.0	63.2	6.54	a
10.35		25	10.5	13.0	3.4	13.9	33.0	7.8	2.00	N.S.
9.35	C	25	13.8	18.0	4.9	21.0	32.0	8.9	3.55	a
8:35		25	21.2	24.0	6.3	40.5	86.0	22.8	4.08	a
14:35		25	8.8	11.0	3.0	15.2	12.0	3.4	7.03	a
12:35	D	25	10.2	15.0	3.5	22.6	29.0	7.7	7.34	a
10:35		25	14.2	14.0	3.5	28.1	28.0	8.3	7.72	a
10:35		25	9.3	6.0	1.6	12.0	5.0	0.7	7.86	a
8:35	E	25	11.6	5.0	1.2	14.4	5.0	1.6	6.93	a
6:35		25	14.0	9.0	1.7	19.0	7.0	2.2	8.14	a

N.S. Not significant at 5% level.
a Significant at the 1% level.

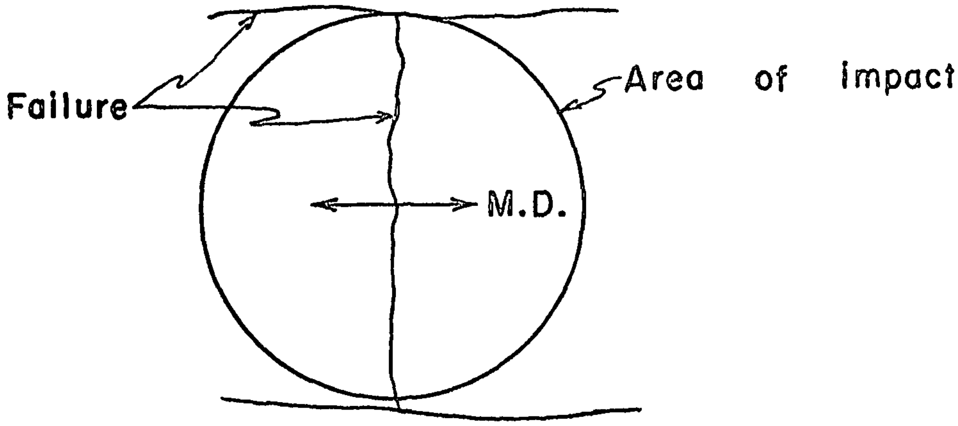


Figure 11. Characteristic Failure Pattern in Couch-Muldoon Specimens

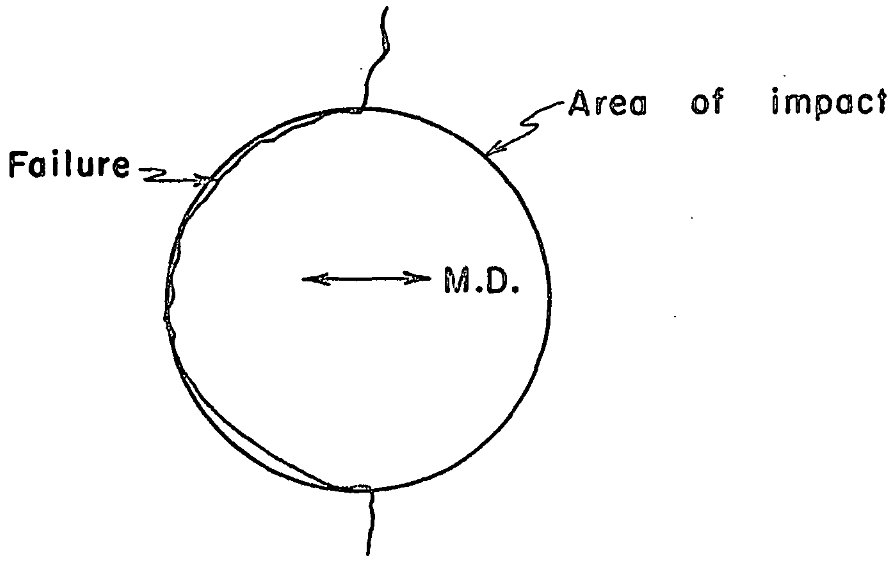


Figure 12. Characteristic Failure Pattern in Couch-Muldoon Specimens

release which has a small impact area but the failure patterns also occurred when testing with the orifice release.

Relationship of Drop Height to Drop Number

It may be of interest to develop from the test data of Table III a relationship between the number of drops required to produce failure and the drop height of the balls. An inspection of the test results of Table III suggests that the relationship may be an inverse power function since the drop number increases at an increasing rate as the drop height is reduced at a constant rate. The proof that an inverse power function is the relationship between the drop number and the drop height may be obtained by plotting the drop height *versus* the drop number on log-log graph paper. The resulting curve of an inverse power function on log-log paper is a straight line of negative slope. The plot of the drop height *versus* the drop number for the fifty-pound kraft sack paper (Sample A) is presented in Figure 13. It may be seen in Figure 13 that the curve of best fit to the plotted points is a straight line of negative slope. The fit is especially good in the case of the test results from the orifice release. The relationship of the drop height and the drop number of the Couch-Muldoon tester for this sample is of the form:

$$N = \frac{c}{H^a}$$

where N = the drop number required for failure

H = the drop height

c and a = constants

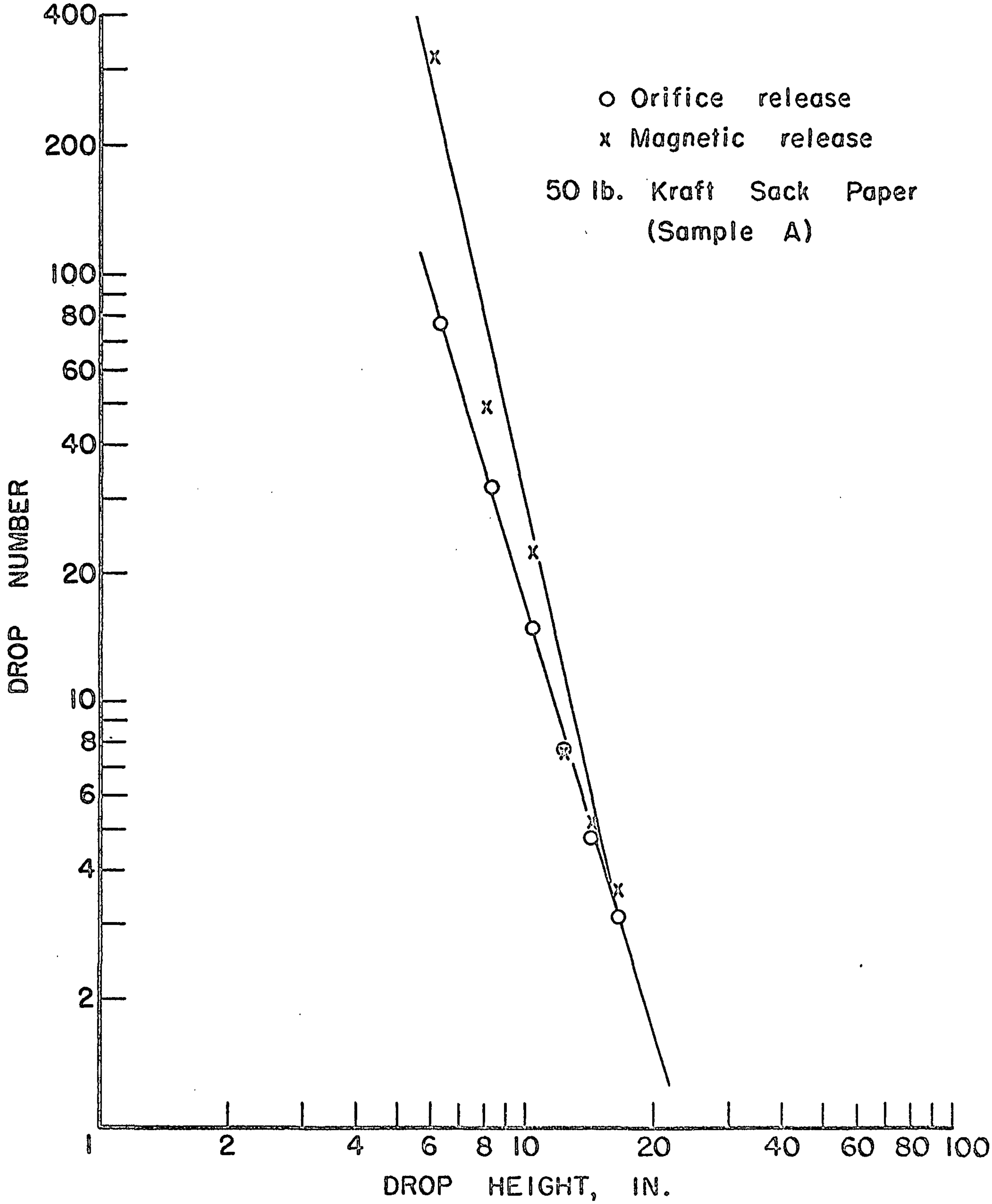


Figure 13. Relationship of Drop Number and Drop Height of the Couch-Muldoon Tester

The formula of the orifice release curve of Figure 13 would be as follows:

$$\log \underline{N} = \log \underline{C} - \underline{a} \log \underline{H}$$

where $\underline{a}$ = the slope of the line = 3.35

$\underline{c}$ = the $\underline{y}$ intercept of the curve = 39,200

$$\therefore \log \underline{N} = \log 39{,}200 - 3.35 \log \underline{H}$$

$$\text{or } \underline{N} = \frac{39{,}200}{\underline{H}^{3.35}}$$

Figure 13 indicates that the constants $\underline{a}$ and $\underline{c}$ are different for the magnetic release and the orifice release and it may be expected that they would be different for each sample tested.

Ten-Day Reproducibility Test

Twenty-five identical specimens of the fifty-pound kraft paper, Sample A, were tested by the orifice release and the magnetic release tester for a period of ten days to determine if the two methods of ball release produced consistent daily results. The results of the testing are tabulated in Table IV. There are differences between the test results of the orifice release and the magnetic release. The average drop number, average range and average standard deviation of the magnetic release were, respectively, 21, 150, and 95% larger than those of the orifice release. The standard deviation of the orifice release is in itself large, indicating a large variability in its test results. The large ranges and standard deviations also were prominent features of the test results presented in Table III.

TABLE IV

DROP NUMBER RESULTS FROM 10-DAY REPRODUCIBILITY TESTS

Day [a]	Orifice Release Average Drop Number	Orifice Release Range	Orifice Release Standard Deviation	Magnetic Release Average Drop Number	Magnetic Release Range	Magnetic Release Standard Deviation
1	6.9	12	3.4	9.9	24	6.7
2	8.5	13	4.1	10.6	32	8.0
3	8.8	14	3.8	7.8	29	6.0
4	6.7	14	3.5	9.6	42	8.4
5	7.8	12	3.4	11.5	63	12.5
6	9.0	14	3.4	8.6	18	4.2
7	9.1	17	3.8	10.1	22	5.7
8	7.6	20	4.3	10.6	23	6.3
9	8.4	13	4.1	10.1	40	8.3
10	7.7	14	3.1	9.6	19	4.9
Average	8.1	14	3.8	9.8	35	7.4

Standard deviation of the population

$$\frac{\underline{S}}{\underline{C_2}} = \frac{3.8}{0.9696} = 3.9 \qquad \frac{\underline{S}}{\underline{C_2}} = \frac{7.4}{0.9696} = 7.6$$

[a] Twenty-five specimens of fifty-pound sack paper, Sample A, were tested each day by both methods of ball release.

The high variability in the test results indicates that a large sample size is required to obtain reliable estimates of the impact fatigue strength of the sample by means of the Couch-Muldoon test. Curves are plotted in Figures 14 and 15 showing the relationship of the sample size to the confidence limits of the mean at confidence levels of 5 and 1%. The formulas of the curves are of the form:

$$\pm \frac{R}{2} = t\sqrt{\frac{\sigma^2}{N}}$$

where $\frac{R}{2}$ = the confidence limits of the mean

t = tabular value of t at $N - 1$

σ = standard deviation

N = the sample size

The population standard deviations calculated from the test results presented in Table IV were used in the above formula to relate the confidence limits on the mean to the sample size.

The curves in Figures 14 and 15 indicate that the magnetic release has larger confidence limits than the orifice release when the same number of specimens are tested. For example, when testing a sample of 25 specimens of Sample A material at a drop height of 12 inches, the mean value of the magnetic release will have confidence limits of ± 3.1 and ± 4.2 drops and the mean of the orifice release will have confidence limits of ± 1.6 and ± 2.2 drops at the 5 and 1% confidence levels.

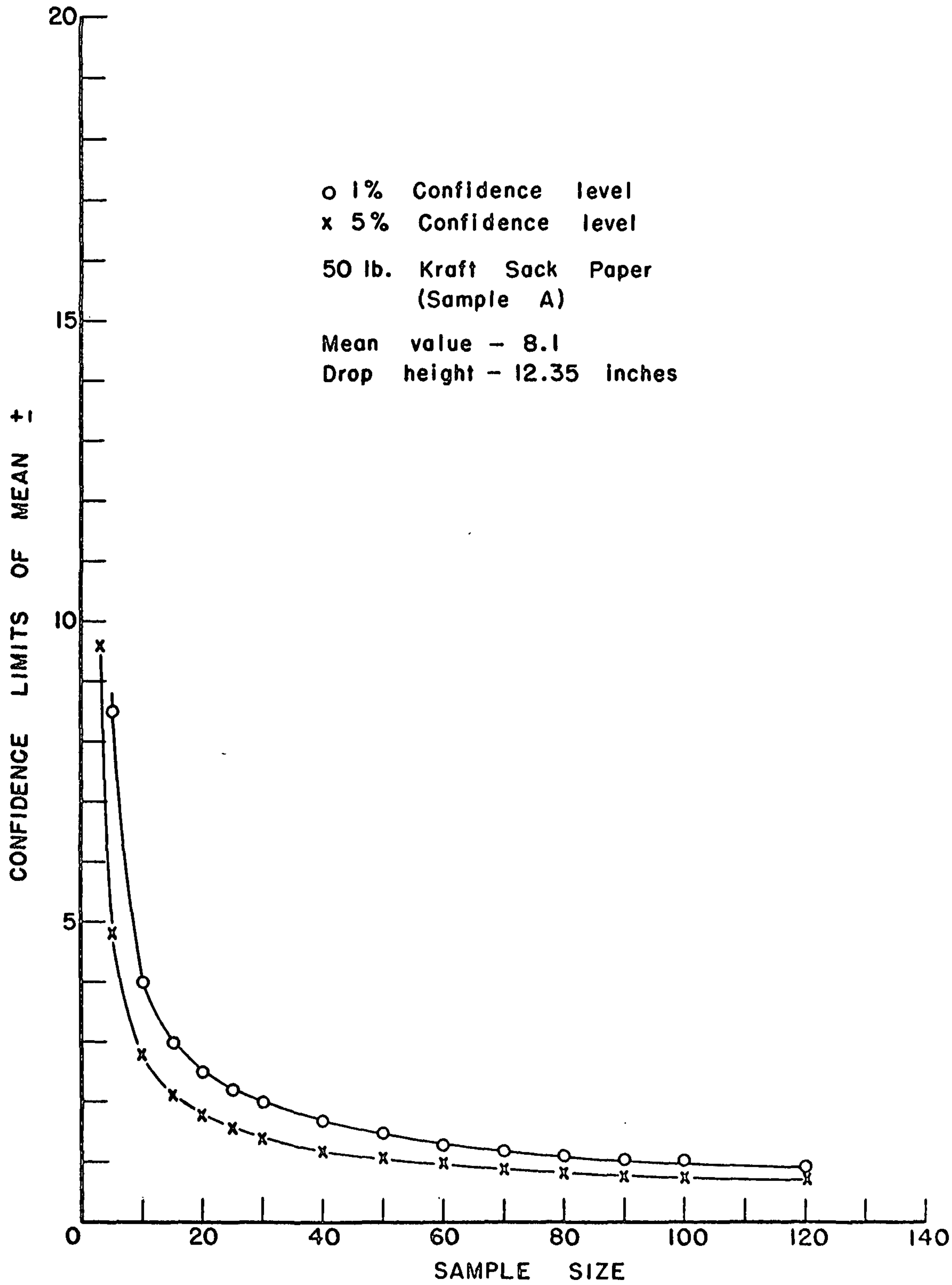


Figure 14. Sample Size Requirements of the Orifice Release

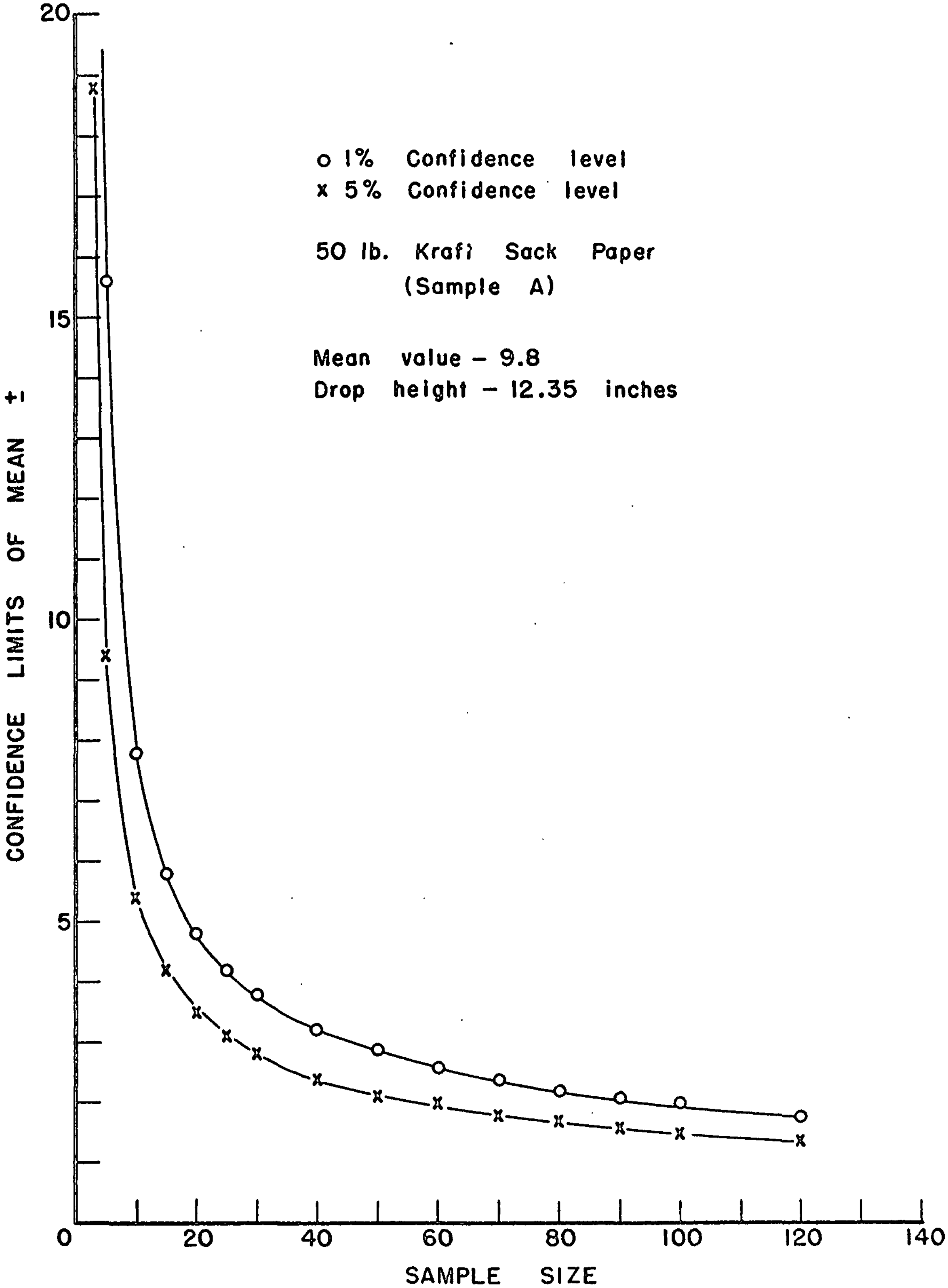


Figure 15. Sample Size Requirements of the Magnetic Release

It may be observed in Figures 14 and 15 that the most economical sample size is one that falls in the bend of the curves. Decreasing the sample size obtains rapidly increasing confidence limits whereas increasing the sample size obtains confidence limits which decrease very slowly.

Statistical analysis of variance reveals that there is no significant difference between any of the ten daily drop number averages obtained by either orifice release or the magnetic release in the ten-day series of tests tabulated in Table IV. This reveals that the orifice release and the magnetic release produce consistent test results on successive days.

Orientation of the Specimen to the Machine Direction of the Paper

The orientation of the machine direction of the paper often has a large influence on the test results of paper. Two hundred specimens of kraft sack paper (Sample A) were randomized and tested so that half of the specimens had the machine direction of the paper parallel to the length of the tester and half of the specimens had the machine direction of the paper perpendicular to the length of the tester. Fifty specimens of each orientation were tested by each method of ball release. The results of the tests are tabulated in Table V.

Statistical analysis of the data indicates that the fiber orientation of the specimens had no significant influence on the test results of the two testers at the 5% level.

TABLE V

NUMBER OF DROPS REQUIRED FOR SPECIMEN FAILURE WITH TWO ORIENTATIONS

OF THE MACHINE DIRECTION OF THE PAPER

	Orifice Release		Magnetic Release	
	In[a]	Across[b]	In	Across
No. of specimens [c]	50.0	50.0	50.0	50.0
Average number of drops	6.4	7.3	9.2	8.9
Range of drops	11.0	15.0	42.0	30.0
Standard deviation	2.4	3.5	7.3	6.5
Value of *t*-test	1.50		0.217	
Significant difference at 5% level	None		None	

[a] In-machine direction of paper parallel to 4-1/2 inch dimension of the specimen.

[b] Across-machine direction of paper parallel to 4-1/2 inch dimension of the specimen.

[c] 50-lb. Kraft sack paper, Specimen A, tested with 12-in. drop.

Rebound of the Ball from the Specimen

The impact ball rebounds away from the specimen after the impact and into the rebound container. A rebound indicates that the specimen restores a portion of the energy it received from the ball as a result of the impact on the specimen. The rebound of the ball away from the specimen might give an indication of how the paper in the specimen was reacting to the impacts. The rebound container was removed from the tester and a long tray was put in its place. Patterns of the rebound were made by lining the bottom of the tray with paper and carbon paper.

Two representative rebound impact patterns obtained when Sample A specimens were tested with impacts from a drop height of 12 inches are presented in Figure 16. It may be of interest to observe that the length of the rebound shows little change until failure occurrs. The first rebound was always shorter than the succeeding rebounds before the failure which was probably due to the nonrecoverable stretch in the paper. It may be seen in Figure 16 that the variation in the length of the rebounds was at most ± 1 inch in 13, which is approximately an 8% variation.

One might anticipate that if the specimen were deteriorating with each successive impact, the distance of the rebound would decrease. Since the energy restored to the system for each impact up to failure appears to be fairly uniform (± 8%), it implies that the paper in the area of impact is not undergoing any progressive deterioration. It is believed, however, that this is an unwarranted implication because it is felt that the rebound may be more a function of the elasticity of the entire specimen area rather than the area

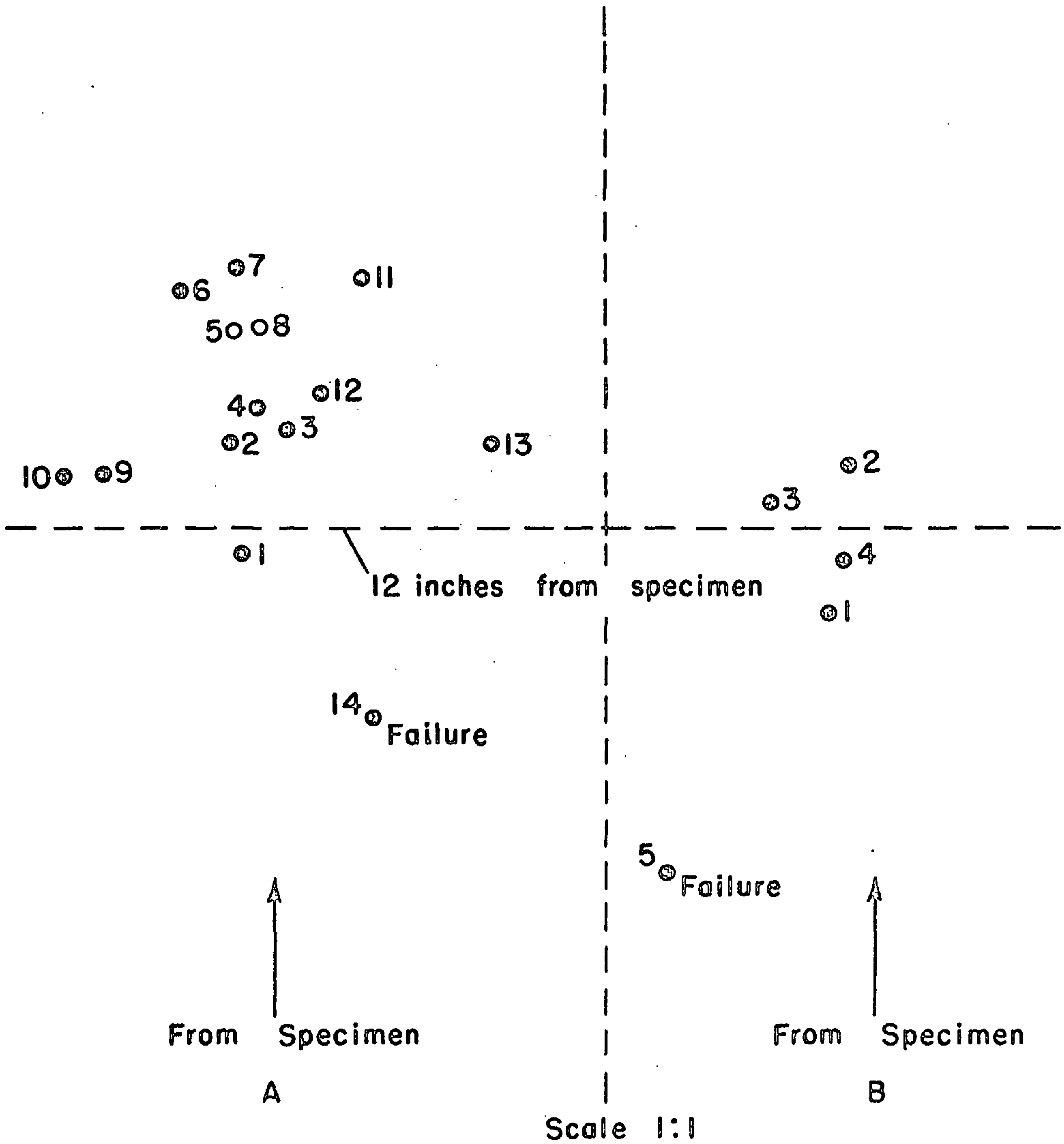


Figure 16. Rebound Impact Patterns

of direct impact. Thus, there could conceivably be a relatively large change in the properties in the area of direct impact without influencing the rebound appreciably since the area of direct impact constitutes only a small portion of the total area on which rebounds depends.

The rebound energy plus the energy absorbed by the specimen should equal the kinetic energy of the impact ball. The energy of the ball at the instant of impact can be calculated from the weight of the ball and the height of the fall. The rebound energy can be expressed as follows:

$$\underline{E} = \frac{\underline{WD}}{2 \sin 2\theta}$$

where $\underline{W}$ = the weight of the ball

$\underline{D}$ = the rebound distance

θ = the angle of the initial rebound path with the horizontal

The above equation may be derived from consideration of the equations for the initial velocity and range used in the elementary theory of projectiles.

In the case of the two rebound patterns in Figure 16, the relationship of input energy, the absorbed energy, and the rebound energy for each impact before failure was as follows:

TABLE VI

DISTRIBUTION OF IMPACT ENERGY OF COUCH-MULDOON TESTER

Pattern		Input Energy	Absorbed Energy	Rebound Energy
A		0.2272 in. lb.	0.0889 in. lb.	0.1383 in. lb.
	%	100%	39% ± 12%	61% ± 8%
B		0.2272 in. lb.	0.0996 in. lb.	0.1276 in. lb.
	%	100%	44% ± 5%	56% ± 4%

CORRELATION WITH THE DROP TEST

The twenty different sack papers used in the fabrication study have been evaluated with the original Couch-Muldoon Impact Fatigue tester and the sacks made from these twenty sack papers have been evaluated with both constant height (4 feet) and progressive height drop tests (2 feet plus 6-inch increments). The results of these three evaluations of the same papers made it possible to compare the drop test and the Couch-Muldoon tester. The correlation coefficients and the error of the estimate, σ_y, were calculated. The error of the estimate is the measure of the scatter of the data about the regression line. It also is a measure of the error that would occur if the number of bag drops that a sack would absorb were predicted from the Couch-Muldoon evaluation of the paper of the sack.

The regression line and the error of the estimate are plotted and presented in Figures 17 and 18. The correlation coefficients of + 0.75 for the constant height correlation and + 0.72 for the progressive height drop correlation show that a fair degree of correlation exists between the Couch-Muldoon tester and the drop test.

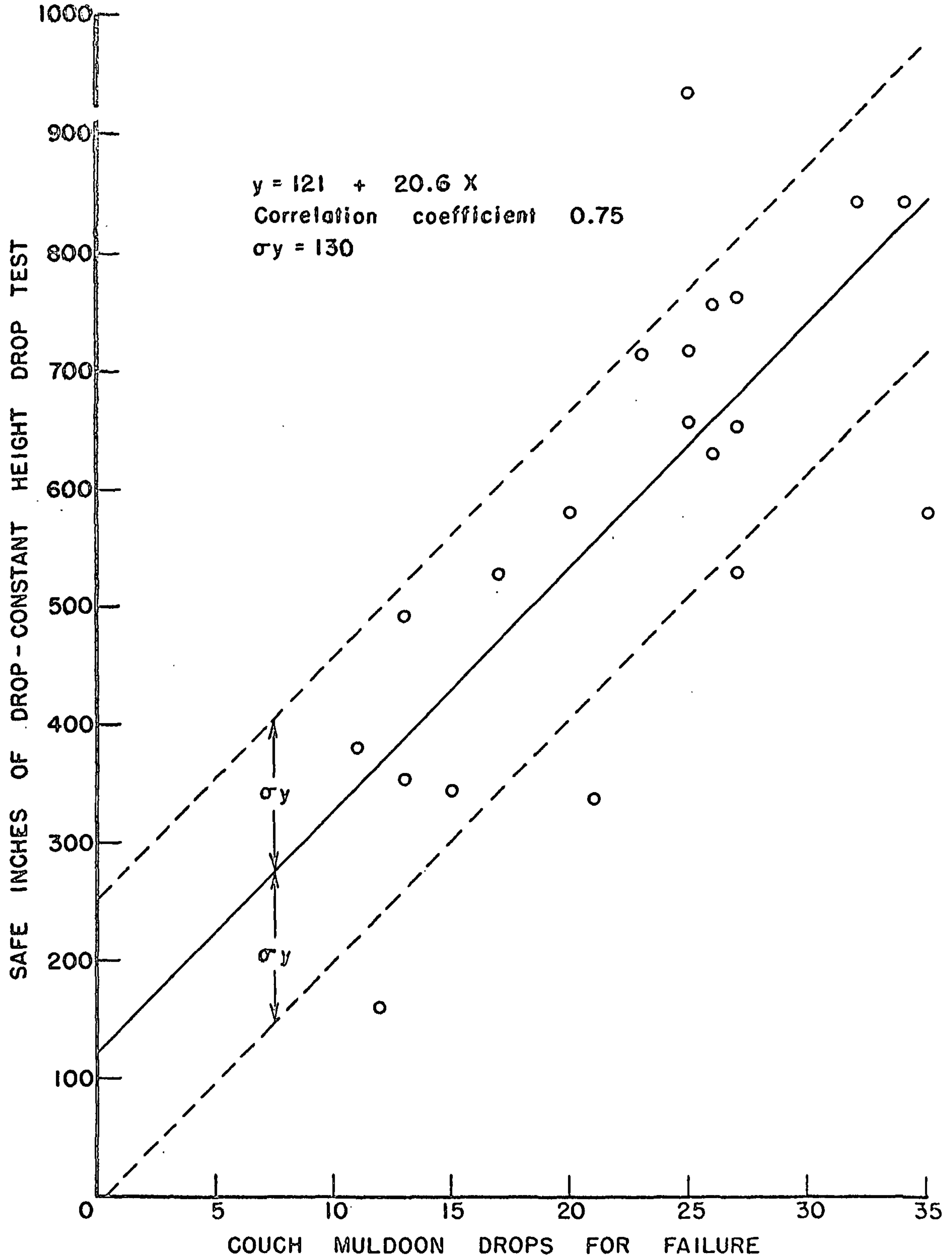


Figure 17. Correlation of the Test Results of the Couch Muldoon Tester with the Results from the Constant Height Drop Test

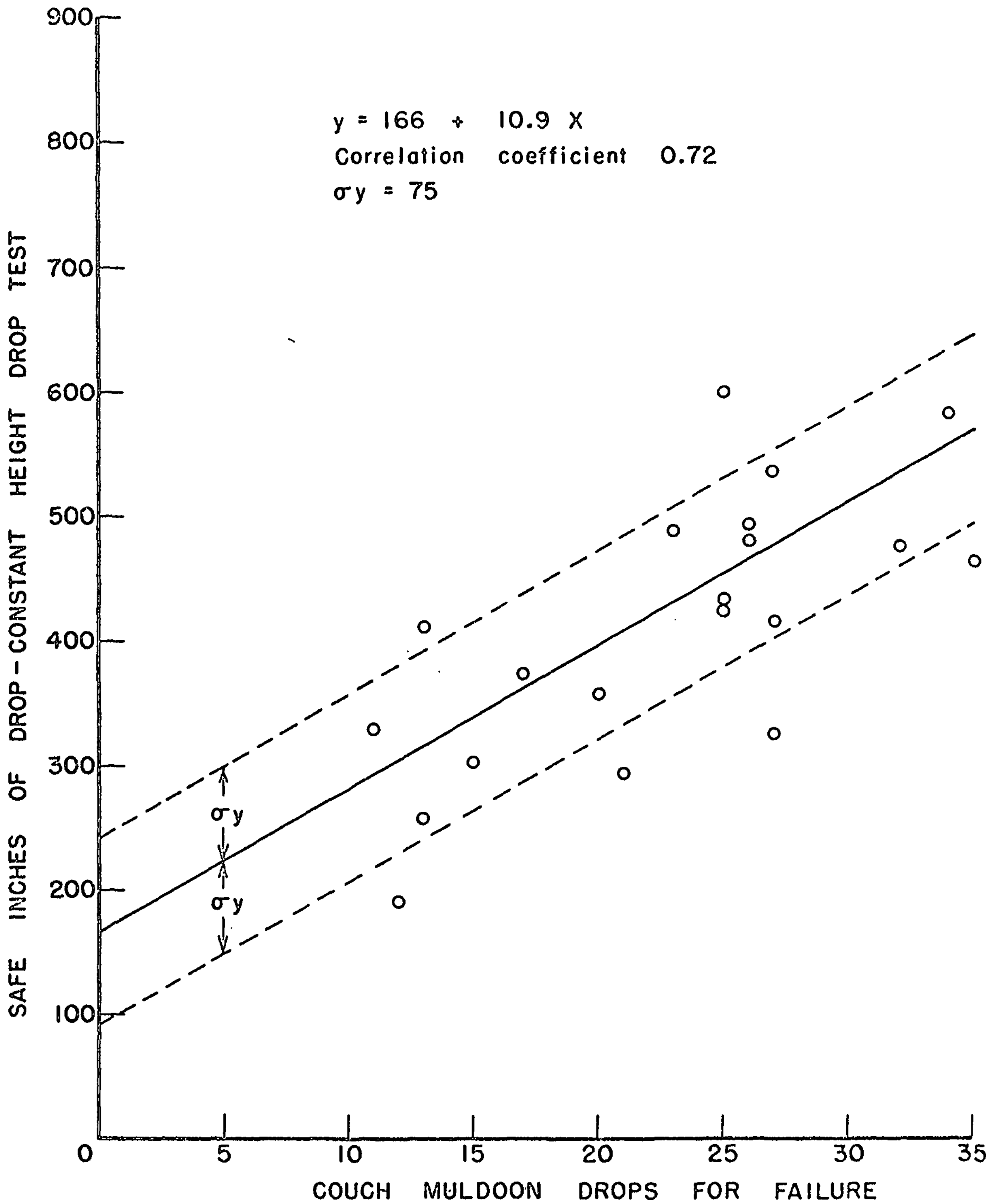


Figure 18. Correlation of the Test Results of the Couch-Muldoon Tester with the Results from the Progressive Height Drop Test

Operational Characteristics of the Couch-Muldoon Tester

It has been previously stated that the impact balls of the tester are dropped at a constant rate of 30 per minute. This factor plus the factors of the sample strength and the drop height of the test determine the length of time required to test a given number of specimens. For example, one hundred specimens of Sample A material have been tested in a period of two hours when using a drop height of twelve inches. The regular operator of the tester normally tested approximately twenty specimens per hour when testing the twenty papers used in the fabrication study at a drop height of ten inches.

The variability of the test results of the Couch-Muldoon tester is large. For example, the coefficients of variation of the test results (the standard deviation expressed as a percentage of the mean) presented in Table IV are 47% for the orifice release tester and 76% for the magnetic release tester. This large variation requires that a large sample must be tested to achieve reliable results (see pages 39 through 42).

Because of the large variability in the test results and because there is no automatic method of determining when the failure occurs, the attention of the operator must be constantly on the specimen for the duration of the test to determine when the test is completed. The tester is not equipped with a counter; consequently, the operator is also required to count the number of impacts needed to produce failure in the specimen.

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